

Gorenstein Rings

Notes for the course MA 842: Topics in Algebra II

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Contents

1	Injective Modules	1
1.1	Basic Properties of Injective Modules	1
1.2	Essential Extensions and Injective Hulls	4
2	Matlis Duality	5
3	Injective Resolutions	8
3.1	Bass's Lemma and ramifications	8
3.2	Modules of finite injective dimension	12

§1 Injective Modules

§§ Basic Properties of Injective Modules

DEFINITION 1.1. Let R be a ring. An R -module E is said to be *injective* if for every inclusion of R -modules $N \hookrightarrow M$ and an R -linear map $N \rightarrow E$, there is an R -linear map $M \rightarrow E$ making

$$\begin{array}{ccccc} 0 & \longrightarrow & N & \longrightarrow & M \\ & & \downarrow & \nearrow \exists & \\ & & E & & \end{array}$$

commute.

An R -module M is said to be *divisible* if

$$\mu_a : M \longrightarrow M \quad m \longmapsto am$$

is surjective for each non-zero-divisor $a \in R$.

REMARK 1.2. It is easy to see that E is injective if and only if given any inclusion of R -modules $N \hookrightarrow M$, the induced map $\text{Hom}_R(M, E) \rightarrow \text{Hom}_R(N, E)$ is surjective. Further, since $\text{Hom}_R(-, E)$ is always left-exact, we have:

An R -module E is injective if and only if $\text{Hom}_R(-, E)$ is an exact functor.

PROPOSITION 1.3. Every injective R -module is divisible.

Proof. Let E be R -injective, $x \in E$, and $a \in R$ a non-zero-divisor. Let $\varphi : R \rightarrow E$ be the unique R -linear map sending $1 \mapsto x$. Since $R \xrightarrow{\mu_a^R} R$ is injective, there is a map $\tilde{\varphi} : R \rightarrow E$ such that $\tilde{\varphi} \circ \mu_a^R = \varphi$. In particular, $a\tilde{\varphi}(1) = x$, whence $\mu_a^E : E \rightarrow E$ is surjective, as desired. ■

THEOREM 1.4 (BAER'S CRITERION). Let R be a ring and E an R -module. Then E is injective if and only if for every ideal $I \trianglelefteq R$ and an R -linear map $f : I \rightarrow E$, there is an R -linear map $F : R \rightarrow E$ such that $F|_I = f$.

Proof. The forward implication is clear. We shall prove the converse. Let $0 \rightarrow N \rightarrow M$ be exact and $f : N \rightarrow E$ be an R -linear map. Consider the poset

$$\Omega = \{(P, g) : N \leq P \leq M \text{ and } g : P \rightarrow E \text{ is } R\text{-linear extending } f\},$$

where $(P, g) \leq (P', g')$ if $P \leq P'$ and $g'|_P = g$. Using Zorn's lemma, choose a maximal element $(P, g) \in \Omega$. We claim that $P = M$. Suppose now and choose some $x \in M \setminus P$. Set $I = (P :_R x) \trianglelefteq R$ and consider the map

$$I \longrightarrow E \quad a \mapsto g(ax).$$

This is well-defined and R -linear, whence it extends to an R -linear map $\varphi : R \rightarrow E$. Let $\alpha = \varphi(1)$ and define $F : P + Rx \rightarrow E$ by $F(p + ax) = g(p) + a\alpha$ for all $p \in P$ and $a \in R$. To see that this is well-defined, note that if $p_1 + a_1x = p_2 + a_2x$, then $a_1 - a_2 \in I$, so that

$$g(p_2) - g(p_1) = g((a_1 - a_2)x) = (a_1 - a_2)\alpha \implies g(p_1) + a_1\alpha = g(p_2) + a_2\alpha.$$

The map F is obviously R -linear and extends g , thereby contradicting the maximality of (P, g) . Hence, $P = M$ and E is injective. ■

COROLLARY 1.5. An R -module E is injective if and only if $\text{Ext}_R^1(R/I, E) = 0$ for all ideals $I \trianglelefteq R$. ■

REMARK 1.6. We note that it is not sufficient to check the equivalent condition of Theorem 1.4 for finitely generated ideals. Indeed, let $R = \mathcal{O}(\mathbb{C})$ the ring of entire functions, or $R = \mathcal{O}_{\overline{\mathbb{Q}}}$ the ring of algebraic integers in \mathbb{C} . It is known that R is a non-Noetherian Bézout domain. As such, due to Interlude 1.12, there is a family of R -injectives $\{E_i\}_{i=1}^{\infty}$ such that $E = \bigoplus_i E_i$ is not injective.

Since each E_i is injective, it is divisible, consequently, E is a divisible R -module. Moreover, since R is a Bézout domain, every finitely generated ideal I in R is principal. It follows now that the equivalent condition of Theorem 1.4 holds for E but E is not injective.

PROPOSITION 1.7. Let R be a PID. An R -module E is injective if and only if it is divisible.

Proof. ■

LEMMA 1.8. Let S be an R -algebra and E an injective R -module. Then $\text{Hom}_R(S, E)$ is an injective S -module.

Note. $\text{Hom}_R(S, E)$ is naturally an S -module under the action

$$(s \cdot f)(s') = f(ss') \quad \forall s, s' \in S, f \in \text{Hom}_R(S, E).$$

Proof. Let $0 \rightarrow M' \rightarrow M \rightarrow M'' \rightarrow 0$ be a short exact sequence of S -modules. Using the Hom-Tensor adjunction, we have

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Hom}_S(M'', \text{Hom}_R(S, E)) & \longrightarrow & \text{Hom}_S(M, \text{Hom}_R(S, E)) & \longrightarrow & \text{Hom}_S(M', \text{Hom}_R(S, E)) \longrightarrow 0 \\ & & \parallel & & \parallel & & \parallel \\ 0 & \longrightarrow & \text{Hom}_R(M' \otimes_S S, E) & \longrightarrow & \text{Hom}_R(M \otimes_S S, E) & \longrightarrow & \text{Hom}_R(M'' \otimes_S S, E) \longrightarrow 0 \\ & & \parallel & & \parallel & & \parallel \\ 0 & \longrightarrow & \text{Hom}_R(M', E) & \longrightarrow & \text{Hom}_R(M, E) & \longrightarrow & \text{Hom}_R(M'', E) \longrightarrow 0 \end{array}$$

The exactness of the bottom row is a consequence of the R -injectivity of E . Thus the top row is exact and we have our desideratum. ■

THEOREM 1.9. Every R -module can be embedded inside an R -injective.

Proof. First, we show this for $R = \mathbb{Z}$. Let M be a \mathbb{Z} -module, then $M \cong \bigoplus_I \mathbb{Z}/N$ for some submodule N of $\bigoplus_I \mathbb{Z}$. There is a natural inclusion of \mathbb{Z} -modules $\bigoplus_I \mathbb{Z} \hookrightarrow \bigoplus_I \mathbb{Q}$ which induces an inclusion

$$M \cong \frac{\bigoplus_I \mathbb{Z}}{N} \hookrightarrow \frac{\bigoplus_I \mathbb{Q}}{N} =: E$$

Being a quotient of a divisible module, E is divisible and hence \mathbb{Z} -injective.

Now, let R be any ring and M an R -module. Then M is naturally a \mathbb{Z} -module and admits a \mathbb{Z} -linear inclusion $\iota : M \hookrightarrow E$, where E is a \mathbb{Z} -injective. Consider the map

$$\varphi : M \longrightarrow \text{Hom}_{\mathbb{Z}}(R, E) \quad m \longmapsto \varphi_m,$$

where $\varphi_m : R \rightarrow E$ is given by $\varphi_m(r) = f(rm)$. The map φ is obviously R -linear and if $\varphi_m = 0$, then $f(m) = \varphi_m(1) = 0$, i.e., $m = 0$. As a result, φ is injective and we have embedded M inside an injective R -module. ■

COROLLARY 1.10. Let E be an R -module. Then E is injective if and only if every R -linear inclusion $E \hookrightarrow M$ splits.

Proof. Suppose E is injective.

$$\begin{array}{ccccc} 0 & \longrightarrow & E & \longrightarrow & M \\ & & \parallel & \nearrow \exists & \\ & & E & & \end{array}$$

The above diagram constructs a splitting of $E \hookrightarrow M$.

Conversely, suppose every R -linear inclusion $E \hookrightarrow M$ splits. Due to Theorem 1.9, we may choose M to be injective, so that E is a direct summand of M , whence E is injective. ■

PROPOSITION 1.11. Let R be a Noetherian ring. A direct sum of injective R -modules is injective.

Proof. Let $\{E_\lambda\}_{\lambda \in \Lambda}$ be a collection of R -injectives and $E = \bigoplus_{\lambda \in \Lambda} E_\lambda$. Let $I \triangleleft R$ be a non-zero proper ideal and $f : I \rightarrow E$ an R -linear map. Since I is finitely generated, its image under f is finitely generated in E . Consequently, there is a finite subset $\Lambda_0 \subseteq \Lambda$ such that $f(I) \subseteq \bigoplus_{\lambda \in \Lambda_0} E_\lambda = E_0$. Being a finite direct sum of injectives, E_0 is injective and hence there is a map $F : R \rightarrow E_0$ extending $f : I \rightarrow E_0$. Composing F with the natural inclusion $E_0 \hookrightarrow E$, we obtain our desired extension of f . It now follows from Theorem 1.4 that E is an injective R -module. ■

INTERLUDE 1.12 (BASS-PAPP CONSTRUCTION). Let R be a non-Noetherian ring. Choose a strictly increasing chain of proper non-zero ideals

$$0 \neq I_1 \subsetneq I_2 \subsetneq \cdots$$

For each $n \geq 1$, choose an injective module E_n containing R/I_n , and set $E = \bigoplus_n E_n$. We contend that E is not R -injective.

Let $I = \bigcup_n I_n$. Since each I_n is proper, so is I . Let $f : I \rightarrow E$ be the map given by

$$f(x) = (x \bmod I_1, x \bmod I_2, \dots).$$

If E were injective, then there must exist a map $F : R \rightarrow E$ extending f . Suppose $F(1) = (x_1, x_2, \dots)$. There is a positive integer N such that $x_n = 0$ for all $n \geq N$. Choose $x \in I_{N+1} \setminus I_N$. Since $x \in I$, we have

$$(xx_1, xx_2, \dots) = F(x) = f(x) = (x \bmod I_1, x \bmod I_2, \dots).$$

In particular, $x \bmod I_N = xx_N = 0$, a contradiction. Thus E is not R -injective.

PROPOSITION 1.13. Let (R, \mathfrak{m}, k) be a Noetherian local ring. If $E \neq 0$ is an finitely generated injective R -module, then R is Artinian.

Proof. We shall show that $\dim R = 0$. Suppose not; we contend that there is a prime $\mathfrak{p} \subsetneq \mathfrak{m}$ such that $\text{Hom}_R(R/\mathfrak{p}, E) \neq 0$. Indeed, if there is a non-maximal prime $\mathfrak{p} \in \text{Ass}_R(E)$, then $R/\mathfrak{p} \hookrightarrow E$, giving us the desideratum. On the other hand, if $\text{Ass}_R(E) = \{\mathfrak{m}\}$, then the composition

$$R/\mathfrak{p} \twoheadrightarrow R/\mathfrak{m} \hookrightarrow E$$

gives a non-zero map $R/\mathfrak{p} \rightarrow E$.

Choose $a \in \mathfrak{m} \setminus \mathfrak{p}$; this is a non-zero-divisor on R/\mathfrak{p} and furnishes an exact sequence

$$0 \rightarrow R/\mathfrak{p} \xrightarrow{a} R/\mathfrak{p}.$$

Applying $\text{Hom}_R(-, E)$, we get a surjection

$$\text{Hom}_R(R/\mathfrak{p}, E) \xrightarrow{a} \text{Hom}_R(R/\mathfrak{p}, E) \rightarrow 0.$$

Note that $\text{Hom}_R(R/\mathfrak{p}, E) \cong (0 :_E \mathfrak{p}) \subseteq E$, is a finite R -module. Due to Nakayama's lemma, we must have that $\text{Hom}_R(R/\mathfrak{p}, E) = 0$, a contradiction. Thus $\dim R = 0$, i.e. R is Artinian. ■

REMARK 1.14. One cannot drop the local condition in Proposition 1.13. This construction makes use of injective hulls. Let k be an algebraically closed field and

$$R = \frac{k[X, Y]}{(X - X^2, Y - XY)}.$$

Note that R is the coordinate ring of the disjoint union of the origin and the line $x = 1$ in \mathbb{A}_k^2 . In particular, $\dim R = 1$, and R is not Artinian.

Let $\mathfrak{m} = (x, y)$ be the maximal ideal corresponding to the origin. Then $R_{\mathfrak{m}} \cong k$, since it is the local ring of an isolated point. Now,

$$E_R(k) \cong E_{R_{\mathfrak{m}}}(k) \cong E_k(k) = k,$$

so that k is a finitely generated injective R -module.

§§ Essential Extensions and Injective Hulls

DEFINITION 1.15. A containment of R -modules $N \subseteq M$ is said to be *essential* if every non-zero submodule of M intersects N non-trivially.

An injective map $\iota : N \hookrightarrow M$ is said to be essential if $\iota(N) \subseteq M$ is essential.

REMARK 1.16. Let $M \subseteq N$ be an essential extension of R -modules and $\varphi : M \hookrightarrow P$ be an R -linear injective map. If φ extends to an R -linear map $\tilde{\varphi} : N \rightarrow P$, then $\tilde{\varphi}$ is injective too. Indeed, if $K = \ker \tilde{\varphi} \neq 0$, then $K \cap M \neq 0$, a contradiction.

PROPOSITION 1.17. Let (R, \mathfrak{m}, k) be a Noetherian local ring. Let M be an Artinian R -module. Then $\text{Soc}_R(M) \subseteq M$ is an essential extension.

Proof. Let $0 \neq K \subseteq M$ be a submodule. Choose $0 \neq x \in K$. Since M is Artinian, the descending chain $Rx \supseteq \mathfrak{m}x \supseteq \mathfrak{m}^2x \supseteq \cdots$ stabilizes. Let $n \geq 0$ be the least positive integer such that $\mathfrak{m}^n x = \mathfrak{m}^{n+1}x$. Due to Nakayama's lemma, $\mathfrak{m}^n x = 0$, whence $n \geq 1$. It follows that $0 \neq \mathfrak{m}^{n-1}x \subseteq \text{Soc}_R(M) \cap K$, as desired. ■

COROLLARY 1.18. Let (R, \mathfrak{m}, k, E) be a Noetherian local ring and M an Artinian R -module. If $\dim_k \text{Soc}_R(M) = d$, then $E_R(M) \cong E^{\oplus d}$.

Proof. Since $\text{Soc}_R(M) \cong k^{\oplus d}$, it is clear that $E_R(\text{Soc}_R(M)) \cong E^{\oplus d}$. The inclusion $\text{Soc}_R(M) \hookrightarrow E^{\oplus d}$ can be extended to M to obtain a commutative diagram:

$$\begin{array}{ccc} & M & \\ \uparrow & \searrow & \\ \text{Soc}_R(M) & \hookrightarrow & E_R(\text{Soc}_R(M)) \cong E^{\oplus d} \end{array}$$

where all maps are inclusion. It follows that $M \hookrightarrow E^{\oplus d}$ is an essential extension. Since $E^{\oplus d}$ is an injective module, we have that $E_R(M) \cong E^{\oplus d}$. ■

§2 Matlis Duality

DEFINITION 2.1. Let (R, \mathfrak{m}, k, E) be a Noetherian local ring. For an R -module M , set $M^\vee = \text{Hom}_R(M, E)$. This is known as the *Matlis dual* of a module.

Clearly $(-)^\vee$ is a contravariant exact functor on the category of R -modules. Note that if $I \subseteq \mathfrak{m}$ is an ideal, then as we have seen earlier,

$$E_{R/I}(k) = \text{Hom}_R(R/I, E) = (R/I)^\vee.$$

In particular, taking $I = \mathfrak{m}$, we see that $k^\vee \cong k$ as R -modules.

LEMMA 2.2. Let (R, \mathfrak{m}, k, E) be a Noetherian local ring. Then

- (1) If $M \neq 0$, then $M^\vee \neq 0$.
- (2) If $\lambda_R(M) < \infty$, then $\lambda_R(M^\vee) \neq 0$. Moreover, $\lambda_R(M) = \lambda_R(M^\vee)$.

Proof. (1) Let $0 \neq x \in M$. If $I = \text{Ann}_R(x)$, then there is a natural inclusion $R/I \hookrightarrow M$ sending $\bar{1} \mapsto x$. Taking the Matlis dual, we have a surjection

$$M^\vee \twoheadrightarrow (R/I)^\vee = E_{R/I}(k) \neq 0,$$

consequently $M^\vee \neq 0$.

- (2) We shall prove both statements by induction on $\lambda_R(M)$. If $\lambda_R(M) = 0$, then $M = 0$, so that $M^\vee = 0$ and we get $\lambda_R(M) = 0 = \lambda_R(M^\vee)$. Suppose now that $0 < \lambda_R(M) < \infty$. Then $\mathfrak{m} \in \text{Ass}_R(M)$, and we have a short exact sequence

$$0 \longrightarrow k \longrightarrow M \longrightarrow N \longrightarrow 0.$$

Since length is additive, $\lambda_R(N) = \lambda_R(M) - 1$; hence the induction hypothesis applies and $\lambda_R(N^\vee) = \lambda_R(N)$. Taking the Matlis dual of the above short exact sequence, we have

$$0 \longrightarrow N^\vee \longrightarrow M^\vee \longrightarrow k^\vee \longrightarrow 0.$$

Since $k^\vee = 0$, we see that

$$\lambda_R(M^\vee) = \lambda_R(N^\vee) + 1 = \lambda_R(N) + 1 = \lambda_R(M),$$

as desired. ■

THEOREM 2.3. Let (R, \mathfrak{m}, k, E) be an Artinian local ring.

- (1) E is a faithful finite R -module.
- (2) The map

$$\mu : R \longrightarrow \text{Hom}_R(E, E) \quad a \longmapsto \mu_a$$

is an isomorphism of R -modules and rings.

- (3) Given a finite R -module M , the natural map

$$\varphi_M : M \longrightarrow M^{\vee\vee} \quad m \longmapsto \text{ev}_m$$

is an isomorphism.

Proof. (1) Suppose $a \in R$ is such that $aE = 0$. Then

$$R^\vee = \text{Hom}_R(R, E) = E = (E :_E a) \cong \text{Hom}_R(R/aR, E) = (R/aR)^\vee.$$

Since R is Artinian, we then have

$$\lambda_R(R) = \lambda_R(R^\vee) = \lambda_R((R/aR)^\vee) = \lambda_R(R/aR) \implies \lambda_R(aR) = 0,$$

consequently, $a = 0$, i.e., E is a faithful R -module.

Next, since R is Artinian, $\mathfrak{m} \in \text{Ass}_R(R)$, consequently, there is an injection $k = R/\mathfrak{m} \hookrightarrow R$. Due to Remark 1.16 extends to an inclusion $E \hookrightarrow R$, consequently, E is a finite R -module.

(2) First note that μ is injective due to (1). But note that

$$\infty > \lambda_R(R) = \lambda_R(R^\vee) = \lambda_R(E) = \lambda_R(E^\vee) = \lambda_R(\operatorname{Hom}_R(E, E)),$$

consequently μ is an isomorphism.

(3) It suffices to show that φ_M is injective since $\lambda_R(M) = \lambda_R(M^{\vee\vee})$. Suppose $0 \neq x \in M$ is such that $\varphi_M(x) = 0$, that is, for all $f \in \operatorname{Hom}_R(M, E)$, $f(x) = 0$. Let $I = \operatorname{Ann}_R(x)$. Now, there is a non-zero map

$$\psi : R/I \twoheadrightarrow R/\mathfrak{m} = k \hookrightarrow E,$$

which extends to a non-zero map $f : M \rightarrow E$ since $R/I \hookrightarrow M$ through $\bar{1} \mapsto x$. Thus, $f(x) = \psi(\bar{1}) \neq 0$, a contradiction. ■

INTERLUDE 2.4 (ON \widehat{R} -MODULES). Let (R, \mathfrak{m}, k) be a local ring and M an R -module such that $\Gamma_{\mathfrak{m}}(M) = M$. We contend that M is an \widehat{R} -module in a natural way. To this end, we need only define $\widehat{a} \cdot m$ for $\widehat{a} \in \widehat{R}$ and $m \in M$.

Let $\widehat{a} = (a_1, a_2, \dots)$, where we are using the isomorphism

$$\widehat{R} = \varprojlim R/\mathfrak{m}^n.$$

Since $\Gamma_{\mathfrak{m}}(M) = M$, there is a positive integer $n \geq 1$ such that $\mathfrak{m}^n m = 0$. Hence, for $k \geq n$, we have $a_k \cdot m = a_n \cdot m$, as $a_k - a_n \in \mathfrak{m}^n$. In light of this, we define $\widehat{a} \cdot m = a_n \cdot m$. We must show that this makes M into an \widehat{R} -module.

Let $m_1, m_2 \in M$ and $\widehat{a} = (a_1, a_2, \dots) \in \widehat{R}$. There are positive integers $n_1, n_2 \geq 1$ such that $\mathfrak{m}^{n_1} m_1 = 0 = \mathfrak{m}^{n_2} m_2$; then $\mathfrak{m}^n m_1 = 0 = \mathfrak{m}^n m_2$ for all $n \geq \max\{n_1, n_2\}$. Hence, for all such $n \geq 1$,

$$\widehat{a} \cdot (m_1 + m_2) = a_n \cdot (m_1 + m_2) = a_n \cdot m_1 + a_n \cdot m_2 = \widehat{a} \cdot m_1 + \widehat{a} \cdot m_2.$$

Next, let $\widehat{a}, \widehat{b} \in \widehat{R}$ and $m \in M$ with

$$\widehat{a} = (a_1, a_2, \dots) \quad \text{and} \quad \widehat{b} = (b_1, b_2, \dots).$$

There is a positive integer n such that $\mathfrak{m}^n m = 0$. Then

$$(\widehat{a} + \widehat{b}) \cdot m = (a_n + b_n) \cdot m = a_n \cdot m + b_n \cdot m = \widehat{a} \cdot m + \widehat{b} \cdot m.$$

Finally, note that $\widehat{b} \cdot m = b_n m$ and $\mathfrak{m}^n (\widehat{b} \cdot m) = 0$, so that

$$\widehat{a} \cdot (\widehat{b} \cdot m) = \widehat{a} \cdot (b_n \cdot m) = a_n \cdot (b_n \cdot m) = (a_n b_n) \cdot m = (\widehat{a}\widehat{b}) \cdot m.$$

This shows that M is indeed an \widehat{R} -module as described above. Further, since $R \rightarrow \widehat{R}$ is the diagonal map, it follows that the \widehat{R} -module structure on M agrees with the R -module structure through the diagonal map. In particular, this means that:

A subset of M is an R -submodule if and only if it is an \widehat{R} -submodule.

As a result, M is Noetherian (resp. Artinian) as an R -module if and only if it is so as an \widehat{R} -module.

INTERLUDE 2.5 (ON MAPS BETWEEN \mathfrak{m} -POWER TORSION MODULES). Again, let (R, \mathfrak{m}, k) be a local ring and suppose M and N are R -modules such that $\Gamma_{\mathfrak{m}}(M) = \Gamma_{\mathfrak{m}}(N)$. By Interlude 2.4, we know that they are \widehat{R} -modules in a natural way. Let $\varphi : M \rightarrow N$ be an R -linear map. We contend that φ is also \widehat{R} -linear. Indeed, let $m \in M$ and $\widehat{a} = (a_1, a_2, \dots) \in \widehat{R}$. There is a positive integer $n \geq 1$ such that $\mathfrak{m}^n m = 0$, and hence, $\mathfrak{m}^n \varphi(m) = 0$. It follows that

$$\varphi(\widehat{a} \cdot m) = \varphi(a_n \cdot m) = a_n \cdot \varphi(m) = \widehat{a} \cdot \varphi(m),$$

as desired.

THEOREM 2.6. Let (R, \mathfrak{m}, k, E) be a Noetherian local ring.

- (1) $\Gamma_{\mathfrak{m}}(E) = E$, and hence E is an \widehat{R} module and for every R -module M , M^{\vee} is \mathfrak{m} -power torsion.
- (2) $E \cong E_{\widehat{R}}(k)$ as \widehat{R} -modules.
- (3) $R^{\vee\vee} = \text{Hom}_R(E, E) \cong \widehat{R}$ as R -modules.
- (4) E is an Artinian R -module.

Proof. (1) That E is an \widehat{R} -module follows immediately from Interlude 2.4. Finally, $M^{\vee} = \text{Hom}_R(M, E)$ is \mathfrak{m} -power torsion because E is so.

- (2) The containment $k \subseteq E$ is an essential extension of R -modules, both of which are \mathfrak{m} -power torsion. Due to Interlude 2.4, it follows that it is an essential extension of \widehat{R} -modules too. Now, due to Remark 1.16, there is a commutative diagram of inclusions

$$\begin{array}{ccc} & E & \\ \uparrow & \searrow & \\ k & \longrightarrow & E_{\widehat{R}}(k), \end{array}$$

where all maps are \widehat{R} -linear. It follows that $E \hookrightarrow E_{\widehat{R}}(k)$ is an essential extension of \widehat{R} -modules, and consequently, an essential extension of R -modules. Since E is R -injective, we must have that the inclusion is an isomorphism of R -modules. Finally, due to Interlude 2.5, this is an isomorphism of \widehat{R} -modules.

- (3)
- (4) Let $M_1 \supseteq M_2 \supseteq \dots$ be a chain of R -submodules in E . There are commutative diagrams

$$\begin{array}{ccc} M_{j+1} & \xhookrightarrow{\iota_{j+1}} & E \\ \downarrow & \searrow \iota_j & \\ M_j & & \end{array}$$

whose Matlis dual furnishes commutative diagrams

$$\begin{array}{ccc} \widehat{R} = E^{\vee} & \xrightarrow{\varphi_j} & M_j^{\vee} \\ & \searrow \varphi_{j+1} & \downarrow \\ & & M_{j+1}^{\vee} \end{array}$$

Note that all Matlis duals are \mathfrak{m} -power torsions and hence due to Interlude 2.5, the φ_j 's are \widehat{R} -linear. Let $I_j = \ker \varphi_j \subseteq \widehat{R}$, which is an ideal. Due to the commutative diagram, it is clear that there is an ascending chain $I_j \subseteq I_{j+1}$. Since \widehat{R} is Noetherian, this chain stabilizes, say $I_n = I_{n+1} = \dots$

Then due to the first isomorphism theorem, $M_j^{\vee} \twoheadrightarrow M_{j+1}^{\vee}$ is an isomorphism for all $j \geq n$. Let $C_j = \text{coker}(M_{j+1} \hookrightarrow M_j)$. The exactness of the Matlis dual gives $C_j^{\vee} = 0$, which, due to Lemma 2.2, implies that $C_j = 0$, that is, $M_{j+1} \hookrightarrow M_j$ is an isomorphism for all $j \geq n$, i.e., the descending chain stabilizes, as desired. \blacksquare

THEOREM 2.7 (MATLIS DUALITY, VERSION 1). Let (R, \mathfrak{m}, k, E) be a Noetherian local ring. Then there is a bijective correspondence

$$\left\{ \begin{array}{c} \text{isomorphism classes of} \\ \text{finitely generated} \\ \widehat{R}\text{-modules} \end{array} \right\} \begin{array}{c} \xrightarrow{(-)^\vee} \\ \xleftarrow{(-)^\vee} \end{array} \left\{ \begin{array}{c} \text{isomorphism classes of} \\ \text{Artinian } R\text{-modules} \end{array} \right\}.$$

Proof. Let M be an Artinian R -module and let $d = \dim_k \text{Soc}_R(M)$. Due to Corollary 1.18, $E_R(M) \cong E^{\oplus d}$, so that there is an inclusion $M \hookrightarrow E^{\oplus d}$, which upon taking the Matlis dual furnishes an \widehat{R} -linear surjection $\widehat{R}^{\oplus d} \twoheadrightarrow M^\vee$. Thus M^\vee is a finite \widehat{R} -module.

Conversely, suppose M is a finite \widehat{R} -module. Thus, there is a surjection $\widehat{R}^{\oplus n} \twoheadrightarrow M$. Taking the Matlis dual, we obtain an injection $M^\vee \hookrightarrow (\widehat{R}^\vee)^{\oplus n}$.

There is a natural “evaluation map” $\text{ev} : M \rightarrow M^{\vee\vee}$, which we shall show is an isomorphism. That ev is injective follows in the same way as Theorem 2.3 (3). Next, since $\lambda_R(M) < \infty$, we have that $\lambda_R(M) = \lambda_R(M^\vee) = \lambda_R(M^{\vee\vee})$, whence ev is an isomorphism. ■

THEOREM 2.8. Let (R, \mathfrak{m}, k, E) be a Noetherian local ring. Then the following are equivalent:

- (1) R is self-injective
- (2) $R \cong E$ as R -modules.
- (3) R is Artinian and $\dim_k \text{Soc}_R(R) = 1$.

Proof. (1) \implies (2) Due to Proposition 1.13, R must be an Artinian local ring, and hence, from Proposition 1.17, $\text{Soc}_R(R) \subseteq R$ is an essential extension. It follows that R is the injective hull of $\text{Soc}_R(R) \cong k^{\oplus d}$ for some positive integer d . Hence, $R \cong E^{\oplus d}$ as R -modules, and comparing lengths, we have

$$\lambda_R(R) = d\lambda_R(E) = d\lambda_R(R^\vee) = d\lambda_R(R),$$

whence $d = 1$ and $R \cong E$.

(2) \implies (3) Due to Theorem 2.6 (4), R is Artinian. Using a length argument as above, we can show that $\dim_k \text{Soc}_R(R) = 1$.

(3) \implies (1) Again, since $k = \text{Soc}_R(R) \subseteq R$ is essential, we have that $R \hookrightarrow E = E_R(k)$. Using a length argument, it follows that this inclusion must be an isomorphism, whence R is self-injective. ■

§3 Injective Resolutions

§§ Bass’s Lemma and ramifications

DEFINITION 3.1. Let M be an R -module. An *injective resolution* for M is an exact complex

$$0 \rightarrow M \rightarrow E^0 \rightarrow E^1 \rightarrow E^2 \rightarrow \cdots,$$

where each E^n is an injective R -module. The resolution is often denoted succinctly as $0 \rightarrow M \rightarrow E^\bullet$.

We say that M has finite injective dimension if M has an injective resolution $0 \rightarrow M \rightarrow E^\bullet$ and an integer $N \geq 0$ such that $E^n = 0$ for $n \geq N$. We define

$$\text{inj dim}_R M = \inf \left\{ n : 0 \rightarrow M \rightarrow E^0 \rightarrow \cdots \rightarrow E^n \rightarrow 0 \text{ is an injective resolution of } M \right\}.$$

If M does not have finite injective dimension, then set $\text{inj dim}_R M = \infty$.

REMARK 3.2. It is possible to create a “canonical” injective resolution by successively taking injective hulls. Set $E^0 = E_R(M)$ and for $i \geq 0$, define

$$E^{i+1} = E_R \left(\text{coker} \left(E^{i-1} \rightarrow E^i \right) \right),$$

with the convention that $E^{-1} = M$. We call this the *minimal injective resolution* of M .

LEMMA 3.3. Let R be a Noetherian ring and $0 \rightarrow M \xrightarrow{\theta} E$ be an inclusion of R -modules with E injective. Then the inclusion is an injective hull of M if and only if

$$\mathrm{Hom}_R(R/\mathfrak{p}, M)_{\mathfrak{p}} \xrightarrow{\theta_{\mathfrak{p}}} \mathrm{Hom}_R(R/\mathfrak{p}, E)_{\mathfrak{p}}$$

is an isomorphism for all $\mathfrak{p} \in \mathrm{Spec}(R)$.

Proof. Owing to the left exactness of $\mathrm{Hom}_R(R/\mathfrak{p}, -)$ and the exactness of localization, the map $\theta_{\mathfrak{p}}$ is injective for each $\mathfrak{p} \in \mathrm{Spec}(R)$. Hence, it suffices to show that E is injective if and only if $\theta_{\mathfrak{p}}$ is surjective for each $\mathfrak{p} \in \mathrm{Spec}(R)$.

Recall that there are canonical isomorphisms

$$\mathrm{Hom}_R(R/\mathfrak{p}, M)_{\mathfrak{p}} \xrightarrow{\sim} \mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), M_{\mathfrak{p}}) \quad \frac{\psi}{s} \mapsto \left(\frac{a}{t} \mapsto \frac{\psi(a)}{st} \right),$$

where we are identifying $\kappa(\mathfrak{p})$ with the quotient field of R/\mathfrak{p} . Hence, surjectivity of $\theta_{\mathfrak{p}}$ is equivalent to the surjectivity of

$$\mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), M_{\mathfrak{p}}) \rightarrow \mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), E_{\mathfrak{p}}).$$

Henceforth, we shall identify M with a submodule of E , so that θ is simply the inclusion map.

Suppose first that $M \xrightarrow{\theta} E$ is an injective hull and let $0 \neq \varphi \in \mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), E_{\mathfrak{p}})$. Using the above isomorphism, we can write $\varphi = \psi/s$ for some $\psi \in \mathrm{Hom}_R(R/\mathfrak{p}, E)$ and $s \in R \setminus \mathfrak{p}$. Let $\psi(\bar{1}) = z \in E$ and $a \in R$ such that $0 \neq az \in M$. Note that $a \in R \setminus \mathfrak{p}$, since $\mathfrak{p} \subseteq \mathrm{Ann}_R(z)$ ¹. Define

$$\bar{\varphi} : R/\mathfrak{p} \rightarrow M \quad \bar{1} \mapsto az.$$

This is well-defined, since \mathfrak{p} annihilates $az \in M$. We claim that

$$\varphi = \frac{\bar{\varphi}}{as} \in \mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), E_{\mathfrak{p}}).$$

Indeed, for $x/t \in \kappa(\mathfrak{p})$ we have

$$\left(\frac{\bar{\varphi}}{as} \right) \left(\frac{x}{t} \right) = \frac{\bar{\varphi}(x)}{ast} = \frac{xaz}{ast} = \frac{xz}{st} = \left(\frac{\psi}{s} \right) \left(\frac{x}{t} \right) = \varphi \left(\frac{x}{t} \right),$$

as desired. This shows that $\mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), M_{\mathfrak{p}}) \rightarrow \mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), E_{\mathfrak{p}})$ is surjective.

Conversely, suppose the aforementioned map is surjective. We shall show that E is the injective hull of M . To this end, it suffices to show that the inclusion $M \subseteq E$ is essential. Let $0 \neq N \subseteq E$ be a submodule and $\mathfrak{p} \in \mathrm{Ass}_R(N)$. There is an injective map

$$0 \rightarrow R/\mathfrak{p} \rightarrow N \quad \bar{1} \mapsto z.$$

Since $\mathfrak{p} = \mathrm{Ann}_R(z)$, it suffices to find $a \in R \setminus \mathfrak{p}$ such that $az \in M$. Consider the map

$$\varphi : \kappa(\mathfrak{p}) \rightarrow E_{\mathfrak{p}} \quad \bar{1} \mapsto z/1.$$

The surjectivity of $\theta_{\mathfrak{p}}$ furnishes a $\psi : \kappa(\mathfrak{p}) \rightarrow M_{\mathfrak{p}}$ such that $\theta_{\mathfrak{p}}(\psi) = \varphi$. In particular, this means that

$$\frac{z}{1} = \varphi(\bar{1}) = \psi(\bar{1}) \in M_{\mathfrak{p}},$$

whence there is some $a \in R \setminus \mathfrak{p}$ such that $az \in M$, as desired. ■

COROLLARY 3.4. Let R be a Noetherian ring and $0 \rightarrow M \rightarrow E^{\bullet}$ be an injective resolution of an R -module M . Then E^{\bullet} is minimal if and only if the natural maps

$$\mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), E_{\mathfrak{p}}^n) \rightarrow \mathrm{Hom}_{R_{\mathfrak{p}}}(\kappa(\mathfrak{p}), E_{\mathfrak{p}}^{n+1})$$

are identically zero for all $n \geq 0$ and for all $\mathfrak{p} \in \mathrm{Spec}(R)$.

¹Note that $\mathfrak{p} = \mathrm{Ann}_R(z)$, for if not, then $\varphi = 0$.

Proof. Let $K^n = \ker(E^n \rightarrow E^{n+1})$. Then there is an exact sequence $0 \rightarrow K^n \rightarrow E^n \rightarrow E^{n+1}$. Using Lemma 3.3, E^n is the injective hull of C^n if and only if

$$\Phi : \text{Hom}_{R_p}(\kappa(\mathfrak{p}), C_p^n) \rightarrow \text{Hom}_{R_p}(\kappa(\mathfrak{p}), E_p^n) \text{ is an isomorphism.}$$

But the left-exactness of Hom and exactness of localization implies that the sequence

$$0 \rightarrow \text{Hom}_{R_p}(\kappa(\mathfrak{p}), C_p^n) \rightarrow \text{Hom}_{R_p}(\kappa(\mathfrak{p}), E_p^n) \rightarrow \text{Hom}_{R_p}(\kappa(\mathfrak{p}), E_p^{n+1})$$

is exact. Thus Φ is an isomorphism if and only if the map $\text{Hom}_{R_p}(\kappa(\mathfrak{p}), E_p^n) \rightarrow \text{Hom}_{R_p}(\kappa(\mathfrak{p}), E_p^{n+1})$ is the zero map, as desired. ■

COROLLARY 3.5. Let R be a Noetherian ring and M an R -module. Let $0 \rightarrow M \rightarrow E^\bullet$ be the minimal injective resolution of M . Then

$$E^j = \bigoplus_{\mathfrak{p}} E_R(R/\mathfrak{p})^{a_j(\mathfrak{p})} \quad \text{and} \quad a_j(\mathfrak{p}) = \dim_{\kappa(\mathfrak{p})} \text{Ext}_{R_p}^j(\kappa(\mathfrak{p}), M_{\mathfrak{p}}).$$

In particular, if M is a finite R -module, $a_j(\mathfrak{p}) < \infty$ for all $j \geq 0$ and $\mathfrak{p} \in \text{Spec}(R)$.

Proof. ■

DEFINITION 3.6. Let R be a Noetherian ring and M a finite R -module. For $j \geq 0$ and $\mathfrak{p} \in \text{Spec}(R)$, define the *j -th Bass number* as

$$\mu_j(\mathfrak{p}, M) = \dim_{\kappa(\mathfrak{p})} \text{Ext}_{R_p}^j(\kappa(\mathfrak{p}), M_{\mathfrak{p}}).$$

REMARK 3.7. We can now justify the name “minimal injective resolution”. In particular, we shall show that the length of the minimal injective resolution is precisely the injective dimension of a module.

Let R be a Noetherian ring and M a finite R -module. Let $0 \rightarrow M \rightarrow E^\bullet$ be the minimal injective resolution in the sense of Remark 3.2. Let $0 \leq \ell \leq \infty$ denote the length of the resolution. Clearly $\text{inj dim}_R M \leq \ell$. If $\text{inj dim}_R M = \infty$, then $\ell \leq \text{inj dim}_R M$ so that $\ell = \text{inj dim}_R M$.

On the other hand, if $\text{inj dim}_R M = n < \infty$, then using this injective resolution to compute the Ext ’s, we see that for $j > n$, and $\mathfrak{p} \in \text{Spec}(R)$,

$$\text{Ext}_R^j(R/\mathfrak{p}, M) = 0 \implies \mu_j(\mathfrak{p}, M) = \dim_{\kappa(\mathfrak{p})} \text{Ext}_{R_p}^j(\kappa(\mathfrak{p}), M_{\mathfrak{p}}) = 0.$$

That is, $E^j = 0$ for all $j > n$ and hence, $\ell \leq n$. It follows that $\ell = \text{inj dim}_R M$.

LEMMA 3.8 (BASS). Let R be a Noetherian ring and M a finite R -module. Let $\mathfrak{p} \subsetneq \mathfrak{q}$ be primes in R such that $\text{ht}(\mathfrak{q}/\mathfrak{p}) = 1$. If for some $j \geq 0$, $\mu_j(\mathfrak{p}, M) \neq 0$, then $\mu_{j+1}(\mathfrak{q}, M) \neq 0$.

Proof. Localizing at \mathfrak{q} , we may assume that (R, \mathfrak{m}, k) is a Noetherian local ring and $\text{ht}(\mathfrak{m}/\mathfrak{p}) = 1$. If $a \in \mathfrak{m} \setminus \mathfrak{p}$, then $\sqrt{\mathfrak{p} + (a)} = \mathfrak{m}$, and we have a short exact sequence

$$0 \rightarrow R/\mathfrak{p} \xrightarrow{a} R/\mathfrak{p} \rightarrow R/(\mathfrak{p} + (a)) \rightarrow 0.$$

This gives rise to a long exact sequence

$$\cdots \rightarrow \text{Ext}_R^j(R/\mathfrak{p}, M) \xrightarrow{a} \text{Ext}_R^j(R/\mathfrak{p}, M) \rightarrow \text{Ext}_R^{j+1}(R/(\mathfrak{p} + (a)), M) \rightarrow \cdots,$$

for all $j \geq 0$.

$$\mu_j(\mathfrak{p}, M) \neq 0 \implies \text{Ext}_{R_p}^j(\kappa(\mathfrak{p}), M_{\mathfrak{p}}) \neq 0 \implies \text{Ext}_R^j(R/\mathfrak{p}, M) \neq 0.$$

Since the Ext ’s are finite R -modules, Nakayama’s lemma implies that $\text{Ext}_R^{j+1}(R/(\mathfrak{p} + (a)), M) \neq 0$.

Since $\sqrt{\mathfrak{p} + (a)} = \mathfrak{m}$, the R -module $R/(\mathfrak{p} + (a))$ is finite Artinian, so that it has a composition series with successive quotients isomorphic to $R/\mathfrak{m} = k$. Now, if $\text{Ext}_R^{j+1}(k, M) \neq 0$, then through the short

exact sequences induced by the composition series, it would follow that $\text{Ext}_R^{j+1}(R/(\mathfrak{p} + (a)), M) = 0$, a contradiction. But since $R \setminus \mathfrak{m}$ consists of only units, we have that

$$0 \neq \text{Ext}_R^{j+1}(k, M) = \text{Ext}_{R_{\mathfrak{m}}}^{j+1}(\kappa(\mathfrak{m}), M_{\mathfrak{m}}),$$

and hence $\mu_{j+1}(\mathfrak{m}, M) \neq 0$. ■

REMARK 3.9. Let R be a Noetherian ring and M a finite R -module.

- (i) If $\mu_i(\mathfrak{p}, M) \neq 0$, then for all primes $\mathfrak{q} \supseteq \mathfrak{p}$ with $\text{ht}(\mathfrak{q}/\mathfrak{p}) = h < \infty$, $\mu_{i+h}(\mathfrak{q}, M) \neq 0$.
- (ii) If (R, \mathfrak{m}, k, E) is a Noetherian local ring with $0 \rightarrow M \rightarrow E^\bullet$ as the minimal injective resolution. If $E^n \neq 0$ and $E^j = 0$ for all $j > n$, then we must have that

$$\mu_n(\mathfrak{p}, M) \neq 0 \iff \mathfrak{p} = \mathfrak{m}.$$

In particular, $E^n = E^{\mu_j(\mathfrak{m}, M)}$.

COROLLARY 3.10. Let (R, \mathfrak{m}, k) be a Noetherian local ring and M a finite R -module. Then

$$\text{inj dim}_R M = \infty \iff \mu_j(\mathfrak{m}, M) \neq 0 \text{ for infinitely many } j \geq 0.$$

Proof. Let $0 \rightarrow M \rightarrow E^\bullet$ denote the minimal injective resolution. Since $\mu_j(\mathfrak{m}, M) = \dim_k \text{Ext}_R^j(k, M)$, it is clear that if the supremum on the right hand side is infinite, then so is the length of the minimal injective resolution, which is the injective dimension of M .

Conversely, if $\text{inj dim}_R M = \infty$, then $E^j \neq 0$ for infinitely many $j \geq 0$. We claim that for every integer $N \geq 0$, there is a $j \geq N$ with $\mu_j(\mathfrak{m}, M) \neq 0$. Indeed, there is an index $i \geq N$ with $E^i \neq 0$. Choose $\mathfrak{p} \in \text{Spec}(R)$ with $\mu_i(\mathfrak{p}, M) \neq 0$. Using Lemma 3.8, setting $j = i + \text{ht}(\mathfrak{m}/\mathfrak{p})$, we must have that $\mu_j(\mathfrak{m}, M) \neq 0$, as desired. ■

THEOREM 3.11. Let (R, \mathfrak{m}, k) be a Noetherian local ring and M a finite R -module. Then

$$\text{inj dim}_R M = \sup \left\{ j : \text{Ext}_R^j(k, M) \neq 0 \right\}.$$

Proof. If $\text{inj dim}_R M = \infty$, then due to Corollary 3.10, $\text{Ext}_R^j(k, M) \neq 0$ for infinitely many $j \geq 0$, so that the supremum on the right hand side is infinite.

Suppose now wthat $\text{inj dim}_R M = n < \infty$. Clearly, $\text{Ext}_R^j(k, M) = 0$ for $j > n$ and hence,

$$\sup \left\{ j : \text{Ext}_R^j(k, M) \neq 0 \right\} \leq n = \text{inj dim}_R M.$$

Let $0 \rightarrow M \rightarrow E^\bullet$ denote the minimal injective resolution. Due to Remark 3.9 (ii), we know that $\text{Ext}_R^n(k, M) \neq 0$, and hence,

$$\sup \left\{ j : \text{Ext}_R^j(k, M) \neq 0 \right\} = n = \text{inj dim}_R M,$$

as desired. ■

COROLLARY 3.12. Let (R, \mathfrak{m}, k) be a regular local ring. If M is a finite R -module, then $\text{inj dim}_R M < \infty$.

Proof. Since R is regular local, $\text{proj dim}_R k < \infty$ and hence for any finite R -module M , $\text{Ext}_R^j(k, M) = 0$ for $j \gg 0$. It follows from Theorem 3.11 that $\text{inj dim}_R M < \infty$. ■

COROLLARY 3.13. Let (R, \mathfrak{m}, k) be a Noetherian local ring. If $\text{inj dim}_R k < \infty$, then R is a regular local ring.

Proof. If $\text{inj dim}_R k < \infty$, then $\text{Ext}_R^j(k, k) = 0$ for $j \gg 0$. Hence, the Betti numbers $\beta_j(k) = \dim_k \text{Ext}_R^j(k, k) = 0$ for $j \gg 0$, whence $\text{proj dim}_R k < \infty$, that is, R is a regular local ring. ■

§§ Modules of finite injective dimension

DEFINITION 3.14. A Noetherian local ring (R, \mathfrak{m}, k) is said to be a *Gorenstein local ring* if $\text{inj dim}_R R < \infty$.

PROPOSITION 3.15. If (R, \mathfrak{m}, k) is a Gorenstein local ring and $\mathfrak{p} \in \text{Spec}(R)$, then $R_{\mathfrak{p}}$ is a Gorenstein local ring.

Proof. Since $\text{inj dim}_R R < \infty$, the minimal injective resolution of R is finite, say of length n :

$$0 \rightarrow R \rightarrow E^0 \rightarrow \cdots \rightarrow E^n \rightarrow 0.$$

Localizing at \mathfrak{p} , one obtains a finite injective resolution of $R_{\mathfrak{p}}$ as an $R_{\mathfrak{p}}$ -module. Thus $R_{\mathfrak{p}}$ is a Gorenstein local ring. ■

This allows us to make the following

DEFINITION 3.16. A Noetherian ring R is said to be *Gorenstein* if $R_{\mathfrak{p}}$ is a Gorenstein local ring for all $\mathfrak{p} \in \text{Spec}(R)$.

Due to Proposition 3.15, every Gorenstein local ring is a Gorenstein ring.

PROPOSITION 3.17. A regular ring is Gorenstein.

Proof. It suffices to show this in the local case. Let (R, \mathfrak{m}, k) be a regular local ring. Then $\text{gl dim } R = \text{proj dim}_R k < \infty$. This means that $\text{Ext}_R^j(k, M) = 0$ for $j \gg 0$; which due to Theorem 3.11 implies $\text{inj dim}_R M < \infty$ for each finite R -module M . In particular, $\text{inj dim}_R R < \infty$, whence R is a Gorenstein local ring, as desired. ■

REMARK 3.18. Note that if R is a Noetherian ring such that $\text{inj dim}_R R < \infty$, then

$$\text{inj dim}_{R_{\mathfrak{p}}} R_{\mathfrak{p}} \leq \text{inj dim}_R R < \infty,$$

so that R is a Gorenstein ring. *What about the converse?*